Metric of Color Borders

Tansley and Boynton (*1*) demonstrated that the distinctness of the border between two colors, as judged by normal subjects, is about the same as that judged by tritanopes. Thus blue cones can make only a small contribution to this judgment, compared with green and red cones. This finding fits well with the relatively large Weber fraction and poor spatial acuity shown by the blue-cone mechanisms (*2*).

The question considered here is whether the metric for such judgments is best viewed as two-dimensional (*1*) or one-dimensional. The importance of this question lies in the fact that a two-dimensional representation, if necessary, implies a qualitatively different form of neural processing than that of a one-dimensional representation. Briefly, the case for a one-dimensional representation is this: it proves possible to characterize each color by a single variable, so the locus of all colors must necessarily be a line in some dimensional space; only if similarities beyond a monotonic relation are present will a representation beyond one dimension be required; a monotonic relation appears sufficient to characterize the data, and, on the basis of available evidence, better describes certain aspects of it than does the two-dimensional representation of Tansley and Boynton (*1*).

After the blue cones are excluded, there are only two independent variables for each of the colors whose apposition forms the border, the photon catches of the green and red cones. The experimental procedure imposed an additional constraint, that each of the 36 colors used had, in effect, the same luminance (*3*). Thus, in terms of its role in contributing to the distinctness of a border, each color could be entirely characterized by a single variable, for example, the photon-catch rate of the green cones.

Using a nonmetric multidimensional scaling program, Tansley and Boynton found that the colors could all be placed along or near a C-shaped line in two dimensions (Fig. 1, inset) so that, in this plane, the rank order of distances between the positions of any two colors was monotonic to the rank order of the perceived distinctness of the border between them, as judged on an arbitrary scale. The relation between position on this line and cone stimulation is shown in Fig. 1. For each color the ordinate plots its position along the C-shaped line and the lower abscissa plots the fractional contribution of the green cones to its luminance, calculated from the dichromatic confusion matrix (*4*). There is a monotonic relation between these variables, as expected.

Tansley and Boynton preferred the two-dimensional representation of their data to the one-dimensional representation because ". . . it permitted an appreciably closer approximation to a proportional relation between distinctness ratings and distance and because both dimensions were susceptible to plausible interpretation" [reference 6 in (*1*)] (*5*). Since nonmetric multidimensional scaling makes use only of the rank of the distinctness judgments, but not of the values along the distinctness scale, the resulting representations provide no direct information regarding the distinctness scale. Furthermore, due mainly to experimental error, data from one-dimensional variables often show a good solution in two dimensions, usually in the form of a C-shaped line (*6*). Thus such shapes in themselves are not evidence, per se, that the metric representation need be more than one-dimensional. However, a second dimension would be unavoidable if the C-shaped curve of Fig. 1 correctly represents the border judgments. This is because it shows the border between colors 1 and 36 to be less distinct than between other combinations (for example, those diametrically opposite, such as 5 and 31). On the other hand, in a one-dimensional representation, such as the ordinate or abscissa of Fig. 1, colors 1 and 36 would necessarily be farthest apart and their border the most distinct. Colors 1 and 36 differ by the greatest amount, both in degree of stimulation of the green cones and in degree of stimulation of the red cones (Fig. 1). If the border between them is actually less distinct than between, for instance, colors 5 and 31, then not only is a two-dimensional representation unavoidable, but there must exist some form of interaction between the signals of different cone types that has not previously been described (that is, some form of cancellation).

The distinctness judgments for the various pairs of colors are not included in (*1*), but similar data in a related study by Ward and Boynton (*7*) suggest that the border between colors such as 1 and 36 is more distinct than that between other pairs, as required if there is only one dimension involved.

In summary, Tansley and Boynton (*1*) demonstrated that blue cones make little if any contribution to the distinctness of color borders. This constraint, that of constant luminance, and that of trichromacy imply that the colors can be

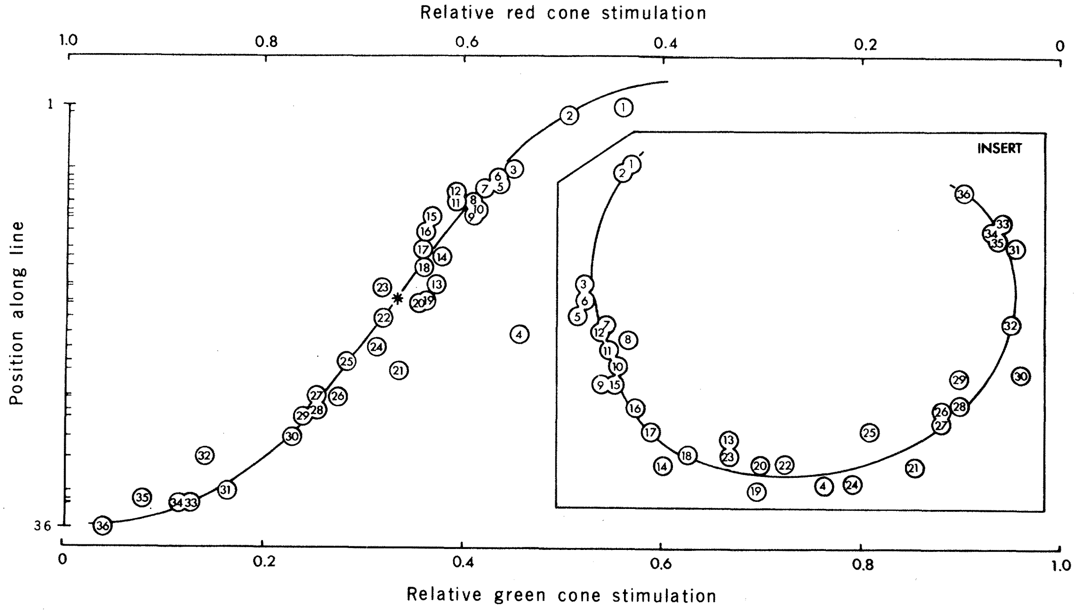

Fig. 1. Results from multidimensional scaling of judged differences among all possible pairs of 36 nonspectral colors (*1*). The C-shaped line in the inset is redrawn from figure 1 in (*1*). The ordinate of the graph plots position along this line. Symbols off the line were assumed to lie on it at the nearest point as determined by constructing a perpendicular. The abscissa is described in the text; the sigmoidal curve through the data points happens to be symmetric about its center (*).

placed along a line. Available evidence suggests that a one-dimensional representation of this line is sufficient to adequately characterize the distinctness of color borders and that the complexities resulting from the introduction of a second dimension may be unnecessary.

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References and Notes

1. B. W. Tansley and R. M. Boynton, *Science* **191**, 954 (1976).
2. W. S. Stiles, *Proc. Natl. Acad. Sci. U.S.A.* **45**, 100 (1959); D. G. Green, *J. Physiol. (London)* **196**, 415 (1968).
3. That the minimally distinct border constraint equalized luminance was demonstrated by G. Wagner and R. M. Boynton [*J. Opt. Soc. Am.* **62**, 1508 (1972)].
4. The calculation is based on the assumption that the three types of dichromats each lack one of the three cone types of normals. The method of calculation is described by G. Wyszecki and W. S. Stiles [*Color Science* (Wiley, New York, 1967), p. 411]. The chromaticity coordinates of the dichromatic confusion points used in these calculations were as follows: $x_p = 0.747$, $y_p = 0.253$; $x_d = 1.530$, $y_d = -0.530$; and $x_t = 0.171$, $y_t = 0$.
5. If a second dimension does exist, then saturation, which was suggested in (*1*), may not be the best name for it since this can vary widely at a single point along the line (for instance, the point on the line that represents those colors lying along the pseudoisochromatic line of the tritanope that passes through the neutral point).

→ R. N. Shepard, *Psychometrika* **39**, 373 (1974).

7. R. Ward and R. M. Boynton, *Vision Res.* **14**, 943 (1974). This is seen most clearly in their experiment 1; the data in experiment 2 are too scattered to permit a firm conclusion either way.

2 August 1976

After reviewing a draft of what eventually became our *Science* report (*1*), Roger Shepard of Stanford University (a pioneer in the development of multidimensional scaling methods) remarked that our work provided the first instance known to him where the use of such procedures has led to a physiological hypothesis. But he was not all smiles. He cautioned us that a helix is often a degenerate form of what is really a one-dimensional solution, as is a C shape in two dimensions. We should beware, he said, of interpreting our results in more dimensions that those for which a plausible interpretation can be given.

At the time, the helical form of the solution in three dimensions excited us far too much (perhaps we thought that the "single helix" would make us famous). We calmed down to two dimensions, but we should have gone all the way. For Rodieck is quite correct in pointing out that the choice of the number of dimensions has significant implications regarding the possible neural interactions underlying chromatic border perception. Our further thinking about the matter has been entirely consistent with his conclusion that a one-dimensional metric is sufficient to account for chromatic border distinctness judgments in a way that makes sense physiologically.

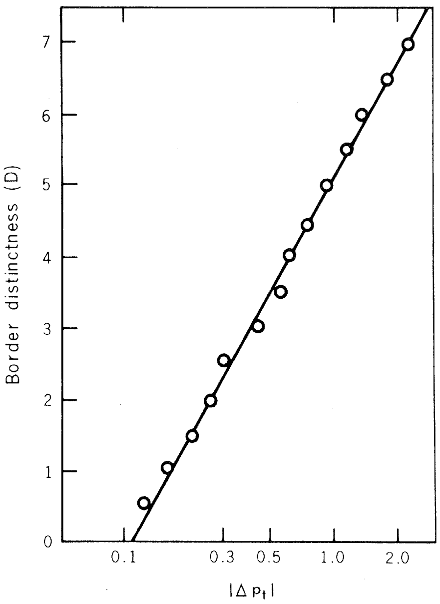

Fig. 1. Border distinctness as a function of absolute difference between tritanopic purity values of pairs of lights.

Valberg and Tansley (*2*) have described a one-dimensional function that reflects the activity of a spectrally opponent mechanism which can account for chromatic border distinctness ratings. Assuming that the mechanism responsible for the perception of chromatic borders in normal observers should be similar to the one that controls color vision more generally for the tritanope, a "tritanopic purity difference function" was calculated. For each of two lights that together make up a bipartite field in which a chromatic border is seen, tritanopic purity, p_t, is given by

$$p_t = k_1 \, (\mathrm{R} - \mathrm{G})/(\mathrm{R} + \mathrm{G})$$

R and G are tristimulus values for a pair of fundamental response functions, *r* and *g*, whose sensitivities (*3*) have been normalized to unity at 570 nm, which is where the tritanope sees a neutral point in the spectrum (*4*). A consequence of this choice of normalizing wavelength is that the function relating chromatic border distinctness to the relative stimulation of R and G cones becomes symmetrical, as Rodieck observed, but did not attempt to explain, in his replot of our distinctness scaling results.

Each spectral distribution has a particular tritanopic purity value associated with it. We have hypothesized that the visual distinctness of a given chromatic border is related to the absolute difference, $|\Delta p_t|$, between the trianopic purity values calculated for each of the two lights.

Subjective border distinctness ratings, D_c, could be predicted by an equation of the form

$$D_c = k_2 \log|\Delta p_t/\Delta p_t|$$

where Δp_t^0 is a threshold value and k_2 is a scaling constant. Figure 1 shows a sample of data taken from an unpublished chromatic border distinctness experiment, similar to the one by Ward and Boynton (*5*), in which spectral lights and distinctness ratings were used. More replications and fewer wavelengths were used in an effort to obtain less noisy data.

Instead of locating the position of each stimulus in a conventional chromaticity diagram, as had been done in a previous analysis (*1*), we have calculated the absolute value of the tritanopic purity difference, $|\Delta p_t|$, for each pair of spectral lights used to generate a chromatic border. We compared these tritanopic purity differences with the visual distinctness ratings that three observers, on average, gave to the borders formed by the apposition of pairs of these spectral lights.

In Fig. 1, each open circle represents the average value of $|\Delta p_t|$ for various pairs of lights that give rise to a chromatic border of a given distinctness (within ± 0.1 distinctness unit). A monotonic transformation of a one-dimensional metric (the logarithm of the tritanopic purity difference) fits closely with the collected distinctness data, as suggested from the earlier multidimensional scaling results to which Rodieck refers (*6*).

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References and Notes

1. B. W. Tansley and R. M. Boynton, *Science* **191**, 954 (1976).
2. A. Valberg and B. W. Tansley, *J. Opt. Soc. Am.*, in press.
3. The functions *r* and *g* were those of P. Walraven [*Vision Res.* **14**, 1339 (1974)]. These are similar, though not identical, to those employed by Rodieck. The value R is proportional to $\int E_\lambda r_\lambda d\lambda$, where E_λ is the special radiance distribution of the light, and integration is across the visible spectrum; G is similarly calculated using *g* (λ).
4. See, for example, W. D. Wright, *Researches in Normal and Defective Colour Vision* (Kimpton, London, 1946).
5. F. Ward and R. M. Boynton, *Vision Res.* **14**, 943 (1974).
6. The details of this metric and its application in other experiments will be described (B. W. Tansley and R. M. Boynton, in preparation)

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